Applications of Mobile LiDAR for Ultra-High Resolution and *GPS-Denied* Terrain Mapping in Planetary Analog Environments

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Introduction: LiDAR scanning systems enable rapid and ultra-high resolution terrain mapping. In this study, we used person-mounted LiDAR systems to acquire data in the Holuhraun region as a planetary analog environment. The Holuhraun Lava Flow-Field was emplaced in Icelandic Highlands (–16.745 °W, 64.911 °N) in 2014–2015. Our study took place in conjunction with the 2022 Rover–Aerial Vehicle Exploration Network (RAVEN) field campaign in an area dominated by fresh spiny pāhoehoe and ʻaʻā-like rubbly lava lobes that are partially mantled by aeolian sand ramps with numerous dune-like forms and ripples composed of sand and silt. The area represents a high-fidelity planetary analog environment, with lava and sedimentary landforms that exhibit morphologies, surface textures, and bedforms that are similar to both Martian and lunar surface environments. The site was also chosen for its accessibility, which facilitated comparisons of LiDAR systems with different capabilities, spatial resolutions, and relative accuracies with the goal of determining the accuracy of GPS-denied terrain mapping and navigation solutions – required for planetary surface exploration – relative to state-of-the art GPS-enabled systems. Data acquired along the same traverses enables us to evaluate the capability of mobile LiDAR technology for future planetary exploration.

Instruments: Two different backpack-mounted mobile LiDAR scanning systems were used. To test the accuracy of a custom SLAM algorithm (KNaCK-SLAM, [4]) Aeries II and OS-1 data were processed both with and without global positioning data, providing an accuracy comparison of GPS-denied mapping to GPS-enabled ground-truth. The Phoenix LiDAR Ranger system was used as a comparison to state-of-the-art.

The Kinematic Navigation and Cartography Knapsack (KNaCK, [1]) is a development test article using velocity-sensing frequency modulated continuous wave (FMCW) LiDAR sensors to evaluate navigation and terrain mapping use in mobile (person- and rover-based) applications.

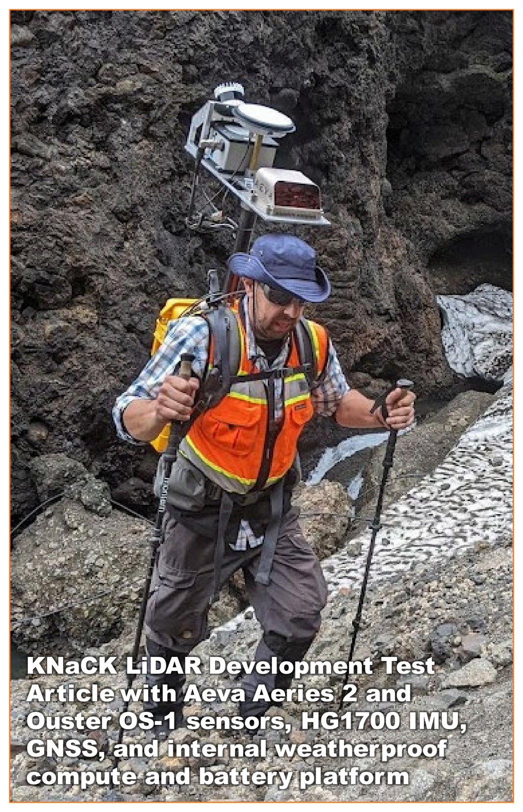
- *LiDARs*
  - ***Aeva Aeries II** FMCW Doppler Velocity Sensing LiDAR [2]*
    - *~120° × 30° FoV; >200 m range*
  - ***Ouster OS-1-64** (Rev 6, [3]) multi-beam flash LiDAR*
    - *360° × 45° FoV; ~100 m range*
  - Both sensors:
    - ~3–5 cm accuracy at ~50 m
    - >1 million points/second;
- *Tactical grade Honeywell HG1700 inertial measurement unit (IMU) with GNSS via a Novatel PwrPak 7.*

Both KNaCK LiDARs broadcast multiple beams allowing for the use of simultaneous localization and mapping (SLAM) algorithms which enable terrain mapping in GPS-denied environments.

The Phoenix LiDAR [5] – Ranger LR system

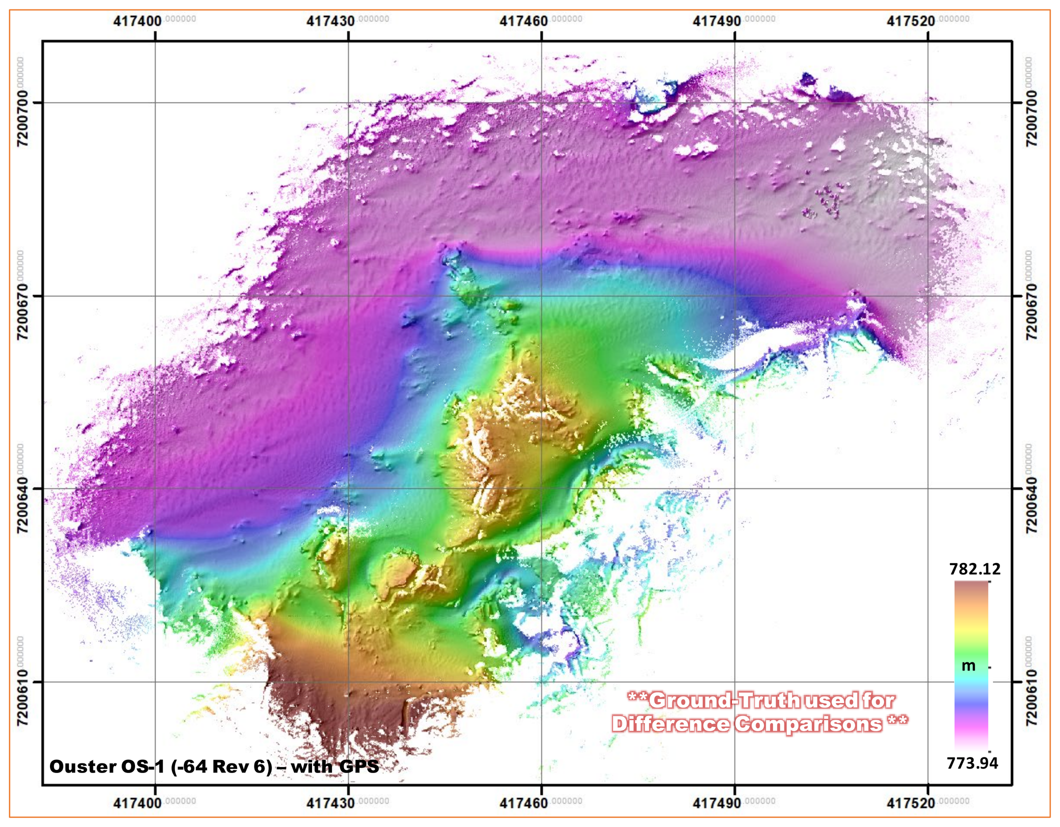
- **Riegl VUX-1HA** sensor
  - 360° single-line sensor
  - sub-cm range precision
  - >>300 m maximum range
  - >1.5 million points/second and 250 lines/second.
- Tactical grade IMU-52 (LN200C) IMU and proprietary point cloud processing software (Spatial Explorer)

The range precision is effectively an order of magnitude better for the VUX-1HA compared to the OS-1-64 (Rev 6). The primary drawback to a single-line scanner, however, is that it cannot be used for SLAM processing, and thus cannot be used for terrain mapping in areas without GPS positioning.

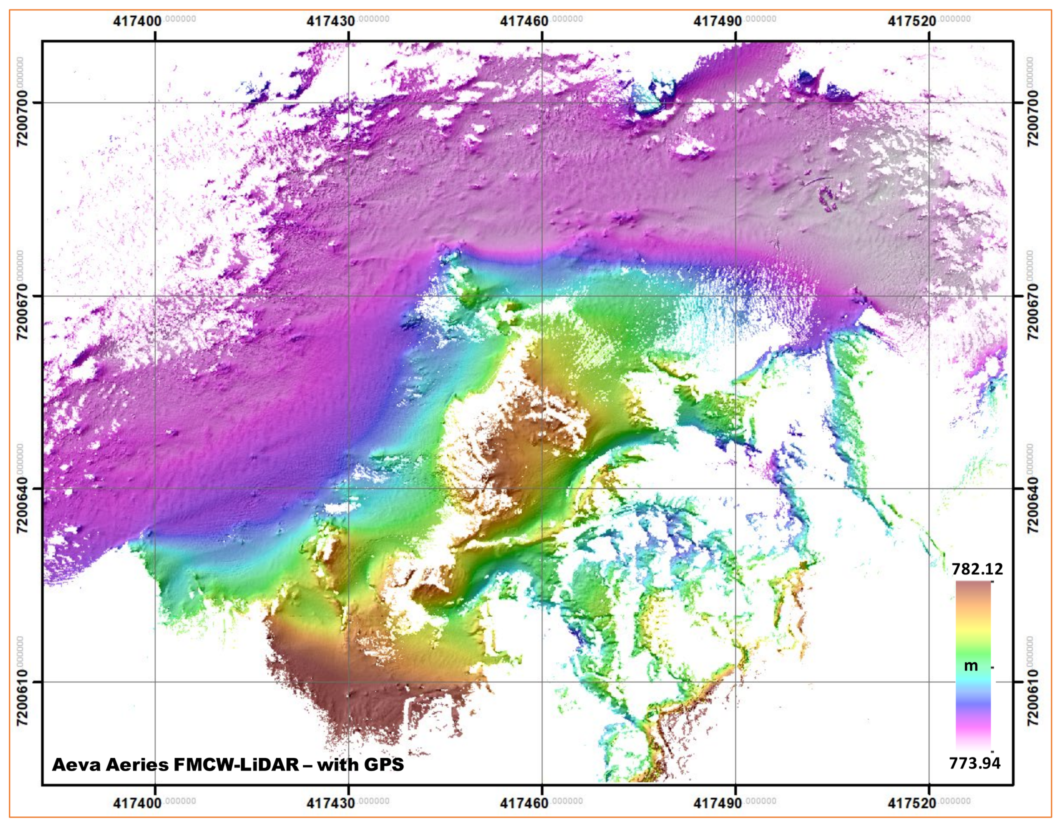

KNaCK LiDAR Development Test Article with Aeva Aeries 2 and Ouster OS-1 sensors, HG1700 IMU, GNSS, and internal weatherproof compute and battery platform


Phoenix LiDAR Ranger LR System with Riegl VUX-1HA sensor, LN200 IMU, GNSS, and external compute and battery platform

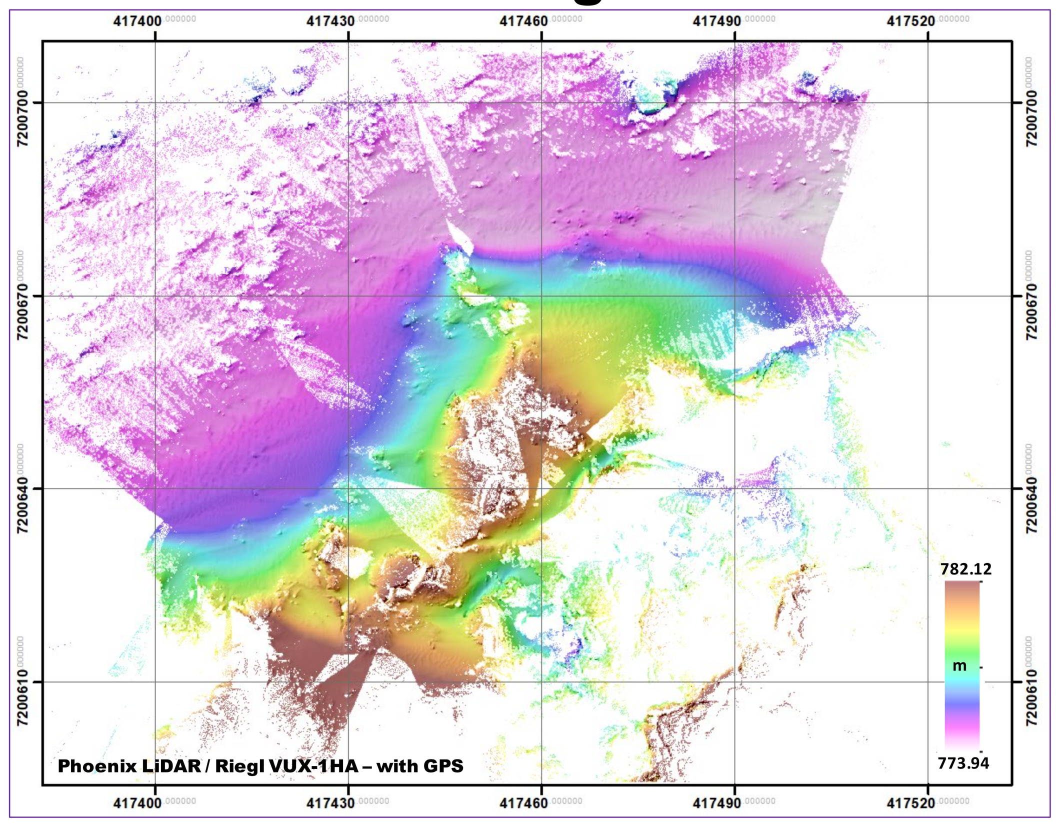
Ouster OS-1 Multi-beam Flash LiDAR



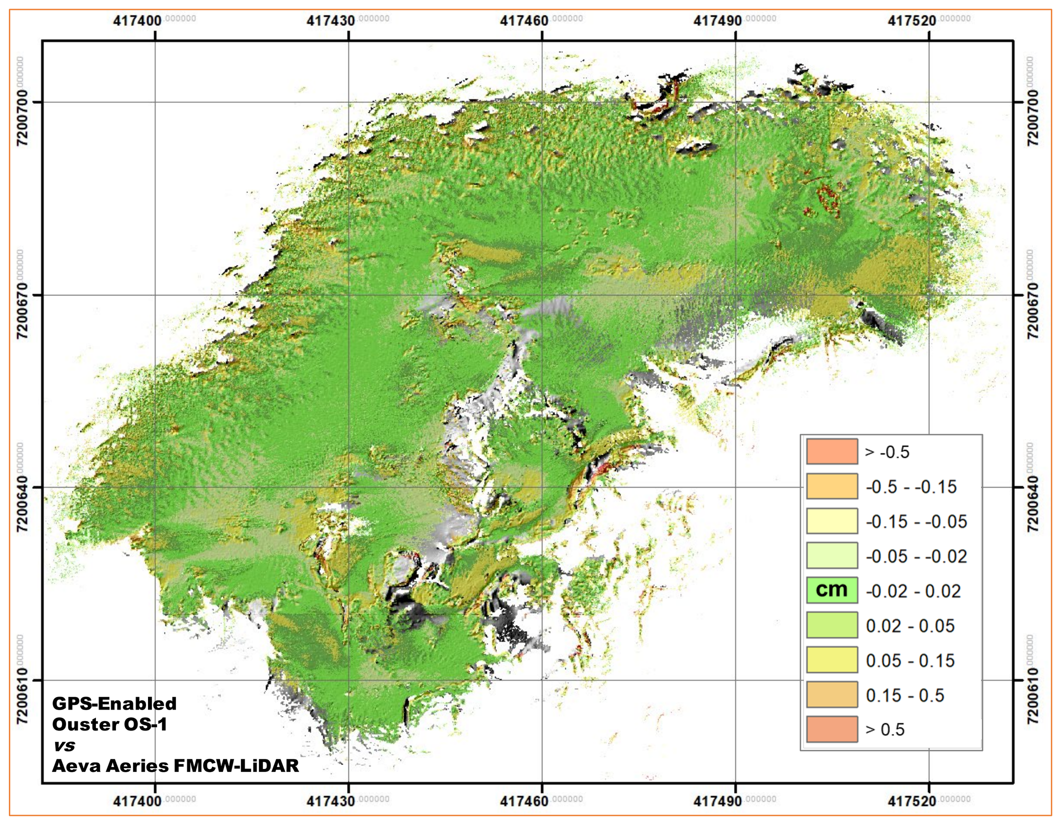
Aeva Aeries FMCW-LiDAR

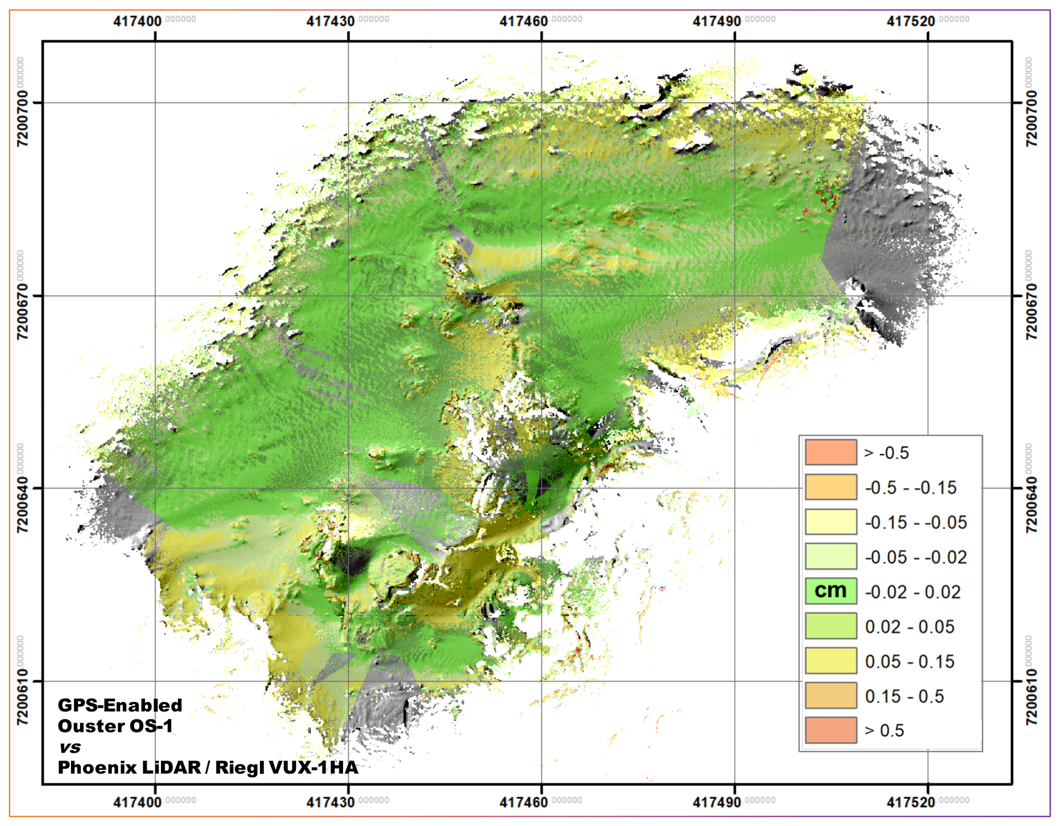


Phoenix LiDAR / Riegl VUX-1HA ToF

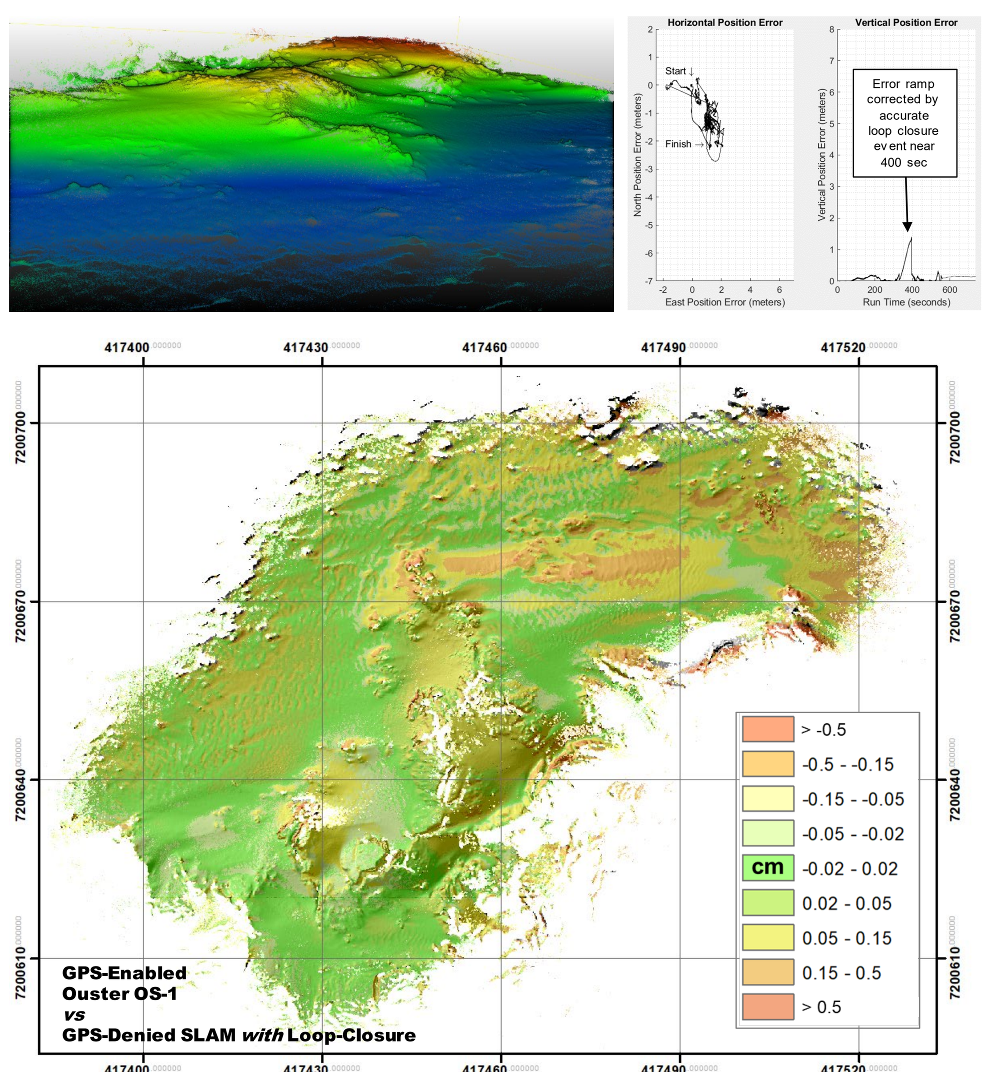


KNaCK LiDAR at Holuhraun Lava Flow Sand-Ramps margin. Note the spectacular similarity as both a Lunar and Mars planetary surface analog.

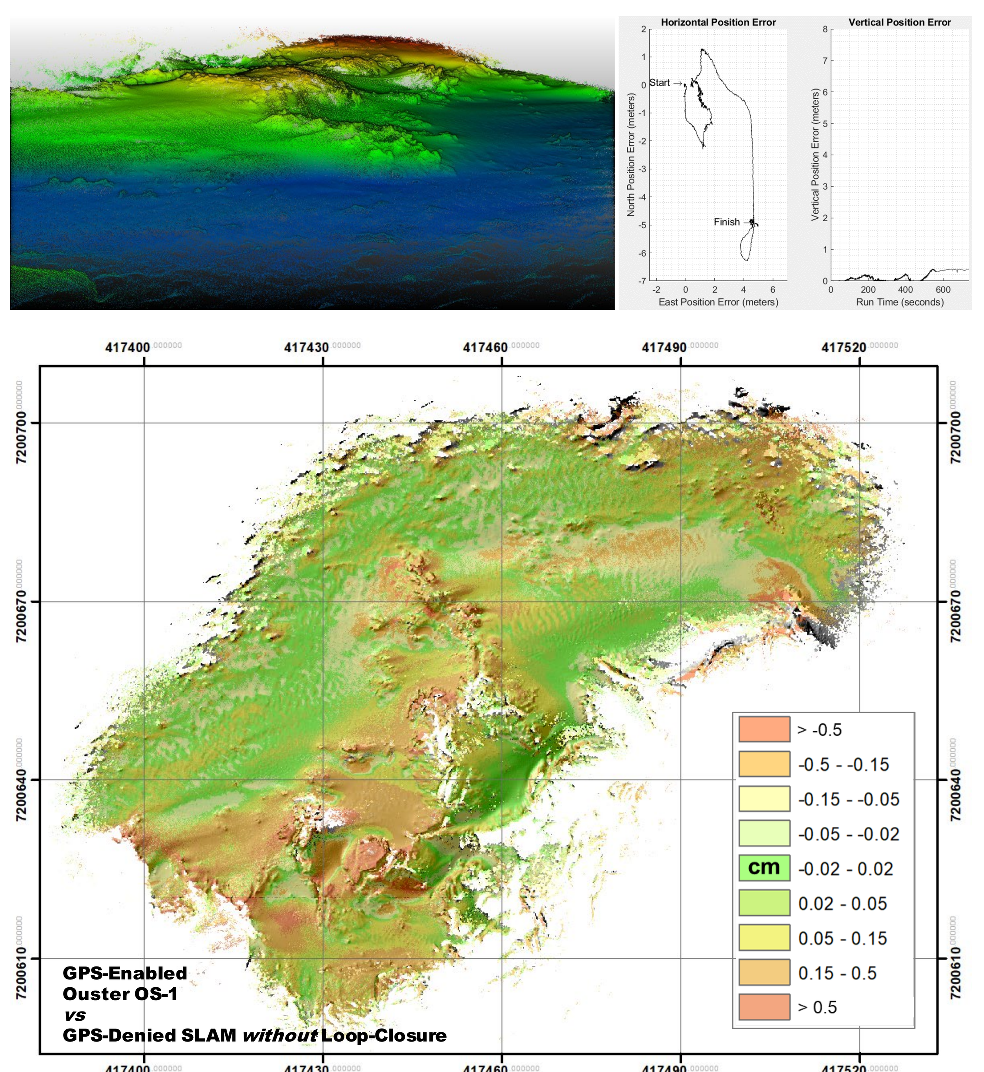




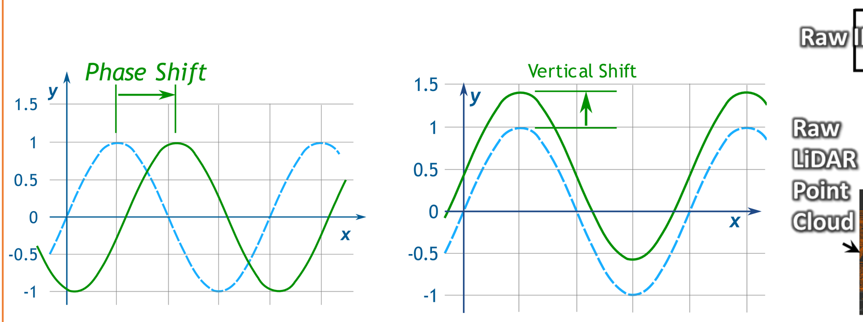
GPS-Denied SLAM *with* Loop-Closure

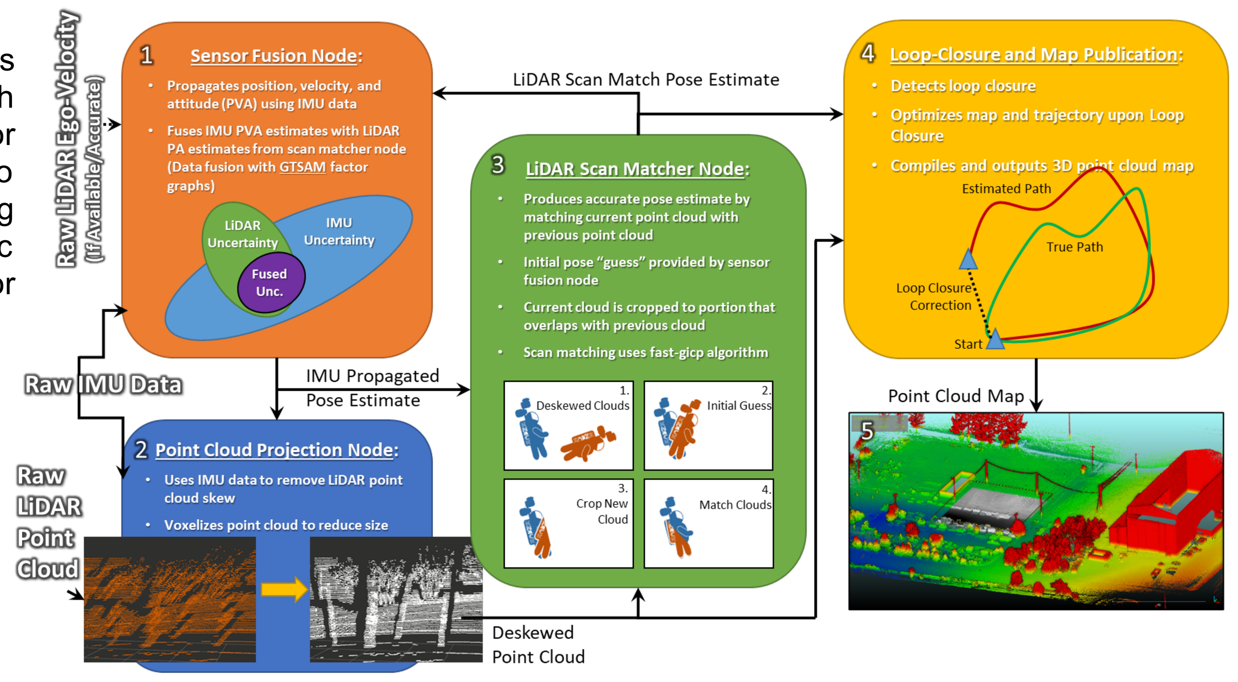


GPS-Denied SLAM *w/out* Loop-Closure



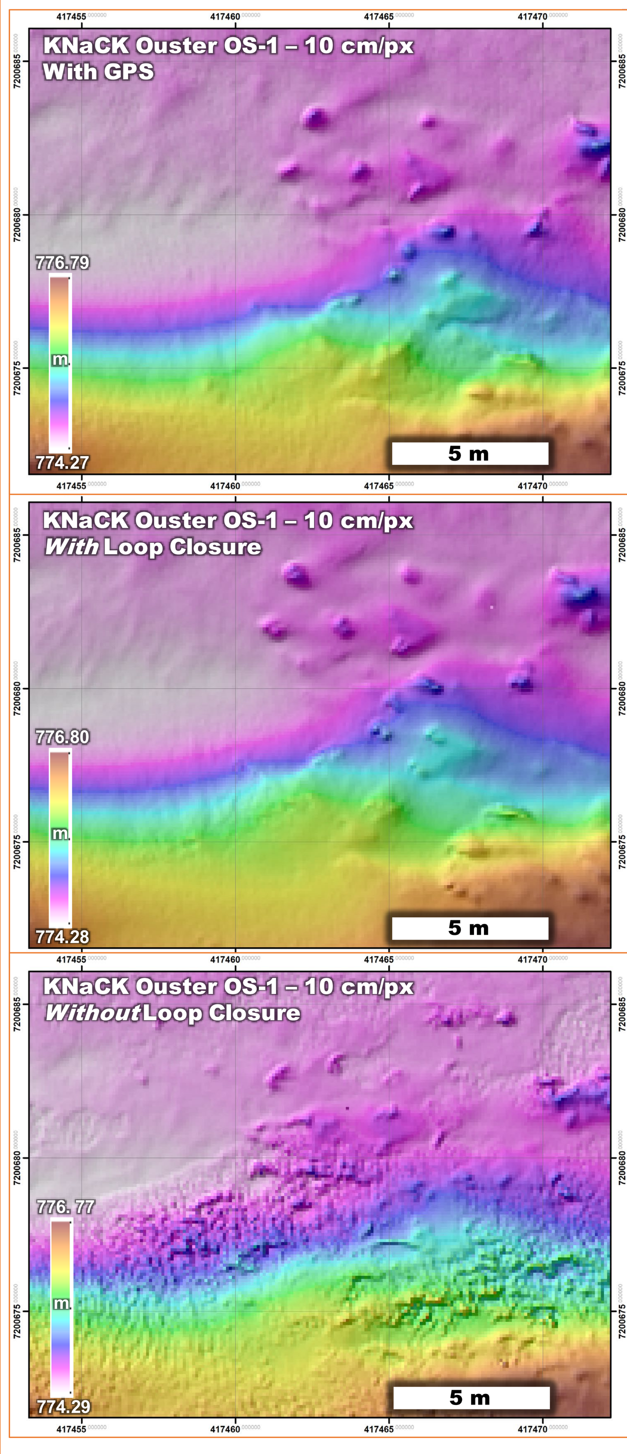
GPS-Denied Mapping Results: In GPS-denied mapping cases, while the map appears to contain no obvious position errors, comparison with GPS-enabled ground-truth from the same sensor shows features out of phase by up to ~1 m due to changing matching alignments. While an outstanding result as it does not rely on GPS, morphologic measurements would be inaccurate and this error would need to be accounted for.

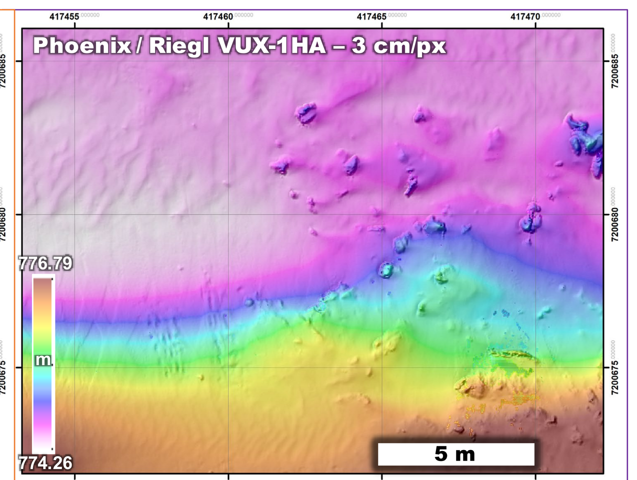




Discussion:

- The Phoenix LiDAR - Ranger LR scanner provides exceptional spatial resolution (3 cm/pixel or better, Fig. 1a), allowing for high-resolution morphologic measurement and terrain characterization but requires GPS and areal coverage can suffer due to LiDAR shadow (mitigated by longer or more complicated traverses).
- Aeries II FMCW-LiDAR offers very good range and coverage (i.e., fewer shadows vs Ranger LR), with the added benefit of multiple scan lines and Doppler velocity measurement—an inherent 6° of freedom (6-dof) "ego"-state estimate informing orientation and position—improving GPS-denied mapping accuracy.
- OS-1 represents a compromise with excellent areal coverage at ~10 cm/pixel resolution (soon to be improved with new Rev-7 sub-cm-precision sensors), and with multiple scan lines allowing for GPS-denied SLAM processing. Figure 2D (GPS-enabled and GPS-denied-loop closure) shows how the accuracy of the data changes due spatial differences in the processed map.





DEM Resolution and Registration Comparison:

A comparison of KNaCK's Ouster OS-1 LiDAR data processed with GPS-enabled and with GPS-denied KNaCK SLAM with and without Loop-Closure is shown at the left. Phoenix LiDAR with the Riegl VUX-1HA LiDAR sensor is shown above (see methods below left).

- **Phoenix LIDAR data:** Displays remarkable clarity of features with 3 cm/pixel spatial resolution (down-sampled from the original ~1 cm point spacing to fill voids). Note the exceptional resolution of the Riegl VUX-1HA that can measure footprints and much more detail in the topography (e.g. tiny ripples).
- **GPS-enabled KNaCK Data:** displays a good compromise between ultra high resolution and feature/hazard detection and is likely suitable for scientific characterization of all but the most subtle features (e.g. tiny ripples).
- **GPS-denied *with* loop closure:** is remarkably similar to the GPS-enable scan, with slight shifts in the spatial position of features and a slight loss of detail.
- **GPS-Denied without loop closure:** displays generally poor discrimination of features and multiple errors. However, the broad topography is consistent, indicating some utility for characterization of slope and traverse paths.

All methods have some utility to aid analysis, but have limitations that need to be accounted for.

Methods: Data from the KNaCK and Ranger systems were collected contemporaneously following an identical ~400 m traverse and GPS signal conditions. Differences in data collection are therefore primarily related to sensor FoV and attributes of the technology used, rather than due to specific operator influence (although operator experience and traverse path can impact end-product quality). Data were pre-processed using scanner-specific software, which all involve the fusing of GPS position, IMU orientation, and LiDAR point-cloud data. Data were georeferenced to UTM28N-NavD88. All point clouds were imported, cleaned to remove isolated points and noise outliers >20 cm, and aligned using CloudCompare [6]. Due to the extremely high density of Ranger LR data, point clouds were subsampled to 1 cm spacing to ease computational load. Point cloud alignment were completed using OS-1 as a reference on 1M pts with final unweighted RMS of 5cm for Ranger LR, 6.2 cm for Aeries II, 6.7 cm for OS-1-noGPS-_LoopClosed, and 7.8cm for OS-1-noGPS_noLoop. (Loop closure is a method in SLAM processing that improves the solution when the sensor can recognize that it has returned to a previously known position). Maps for OS-1 and Aeries II (with and without GPS) and Ranger LR (with GPS) were exported as georeferenced rasters into ArcGIS 10.8 where difference maps were calculated (with no additional georeferencing).

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